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From: Director, Office of Naval Research, Seattle Regional Office, 1107 NE 45th St., Suite 350, Seattle, WA 98105

To: Defense Technical Center, Attn: P. Mawby, 8725 John J. Kingman Rd., Suite 0944, Ft. Belvoir, VA 22060-6218

Subj: RETURNED GRANTEE/CONTRACTOR TECHNICAL REPORTS

1. This confirms our conversations of 27 Feb 97 and 11 Jul 97. Enclosed are a number of technical reports which were returned to our agency for lack of clear distribution availability statement. This confirms that all reports are unclassified and are "APPROVED FOR PUBLIC RELEASE" with no restrictions.

2. Please contact me if you require additional information. My e-mail is *silverr@onr.navy.mil* and my phone is (206) 625-3196.

ROBERT J. SILVERMAN

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SEATTLE, WASHINGTON 98195–1640

Prof. Kristina B. Katsaros
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TEL: (206) 543–9142
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January 2, 1996

Office of Naval Research
Director, Dr. James Case
ONR 322, BCT-1, Room 407-1
800 North Quincy St.
Arlington, Virginia 22217-5660

Dear Sir:

Enclosed please find the final report concerning our research entitled *"SEMAPHORE Field Phase Support"* conducted under grant N00014–93–1–1367 to the University of Washington from the Office of Naval Research.

Sincerely yours,

For Prof. Kristina B. Katsaros

Serhad S. Ataktürk

DR. SERHAD S. ATAKTÜRK

cc: ONR, Seattle, WA
ONR, Washington, D.C.
ONR, Alexandria, Virginia
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SEMAPHORE FIELD PHASE SUPPORT

P.I.: Kristina B. Katsaros

Department of Atmospheric Sciences, Box 351640
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FINAL REPORT
ONR GRANT N00014–93–1–1367

January 2, 1996

SEMAPHORE FIELD PHASE SUPPORT

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This final report concerns our research conducted under grant N00014–93–1–1367 to the University of Washington from the Office of Naval Research for the period between October 1, 1993 and September 30, 1995. Our accomplishments are summarized below.

LONG RANGE OBJECTIVES

Our aim is to improve the understanding of the processes determining the turbulent and radiative fluxes at the sea surface, particularly their dependence on sea state and on mesoscale structures in the planetary boundary layer.

SPECIFIC OBJECTIVE

The objective of the work carried under this grant is to measure in detail the major parameters needed

(*i*) to explain the variability of the turbulent air–sea fluxes of momentum, heat and water vapor with sea state and mesoscale boundary layer structures, and

(*ii*) to test the flux–gradient relations.

ACCOMPLISHMENTS

In order to achieve the goals above, we developed a laboratory for studies of air–sea interaction using the catamaran buoy, *MENTOR* (Figure 1). The specifications of the buoy and its instrumentation are identified in Figure 2. *MENTOR* is not self–propelled therefore, it is transported to the desired site either in tow or on board of another marine vessel and, once at location it is released to drift freely. The power for instruments and recorders are provided by batteries. All acquired data are stored on board in digital format. Periodically, some information vital for recovery and operation of the buoy (such as current time, location, battery voltage and wind speed and direction) is broadcast via an *ARGOS* transmitter.

The track of *MENTOR* during the *SEMAPHORE* (Structure des Exchanges Mer Atmosphere Proprietes des Heterogeneties de L'Ocean leur Repartition) field campaign is illustrated in Figure 3.

It was towed out of Santa Maria, Azores, on October 6, 1993. Following the buoy's release on October 7, a severe storm rapidly influenced the region and the tow vessel was forced to return to harbor. Unfortunately, the instrument tower and the stabilizer of *MENTOR* could not withstand the strong winds and heavy seas for long. Search for the buoy could not be attempted for several days due to stormy conditions and the following efforts were not successful in locating it. Eventually, *MENTOR* was found by a ship on November 17, 1993 and was returned to our possession. Inspection of the buoy showed that the data storage modules had survived this extreme event.

The article by Katsaros *et al* (1994 – included with this report) provides an overall review of this research effort. Technical reports by Drennan and Donelan (1994, 1995 – also included) are based on the analysis of the recovered data set and assess the performance of the *MENTOR* and the quality of the data obtained, respectively.

CONCLUSIONS

The buoy, *MENTOR* was operational for a short period of time and provided some limited data. More importantly, the success during its short–lived mission also provided the proof of a concept that detailed measurements necessary to advance our understanding of the interactions between the oceans and the atmosphere can be carried out with the state–of–the–art instruments from an unattended platform. At the time being, the *MENTOR* is stored in France and requires a new stabilizer and an instrumentation mast before deployment for its next mission.

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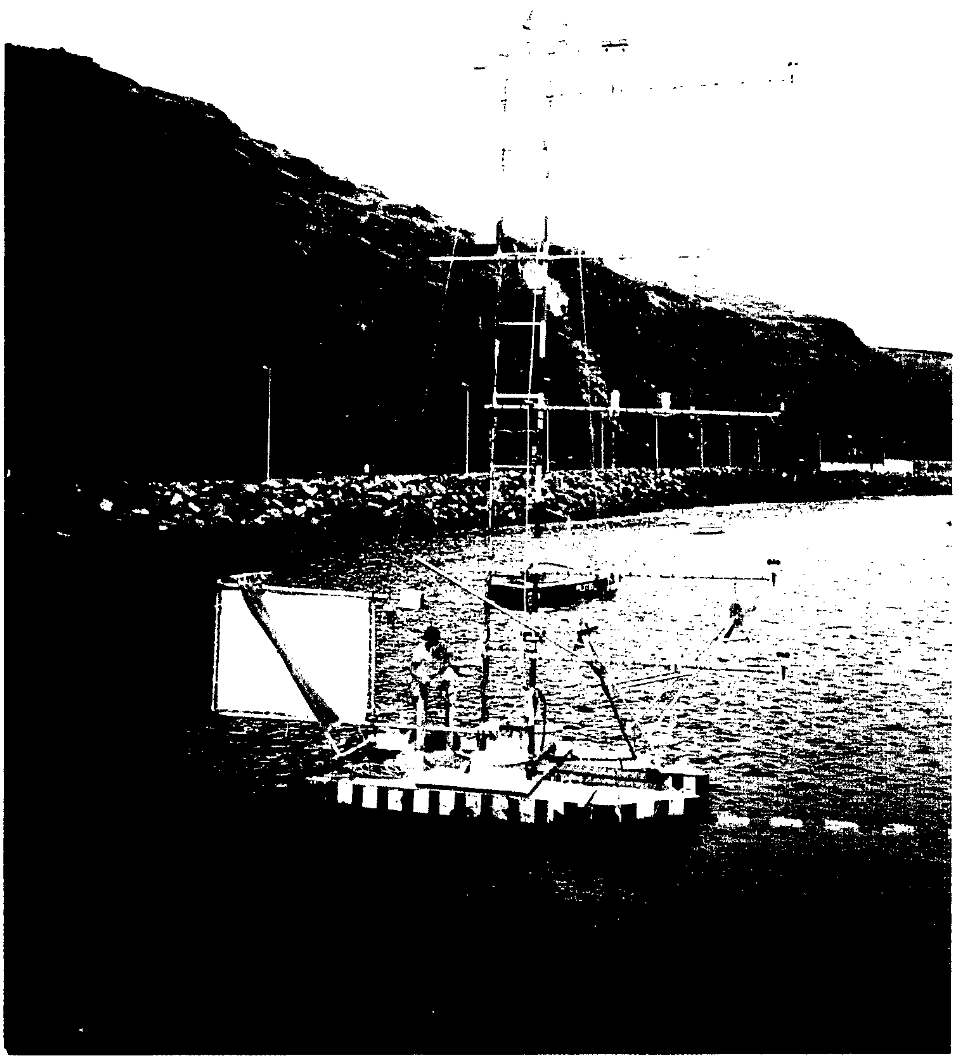
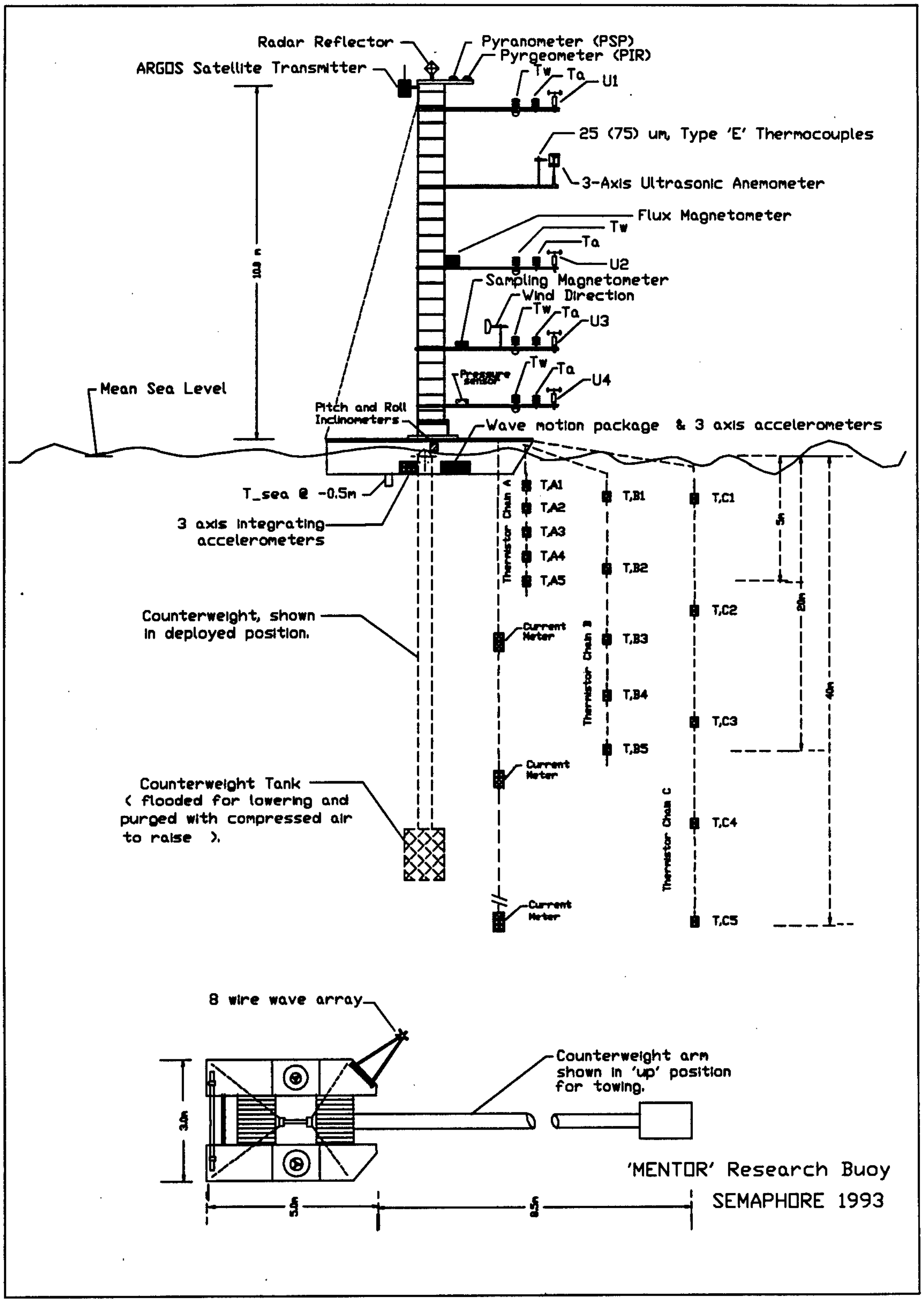
Katsaros, K.B., W.M. Drennan and M.A. Donelan, 1994: Flux gradient measurements from a catamaran buoy in *SEMAPHORE.* In *Proceedings of the Second International Conference on Air–Sea Interaction and on Meteorology and Oceanography of the Coastal Zone,* September 22–27, 1994, Lisbon, Portugal (provided).



THE CATAMARAN BUOY, MENTOR.

FIGURE 4



Radar Reflector
Pyranometer (PSP)
Pyrgeometer (PIR)
ARGOS Satellite Transmitter
Tw
Ta
U1
25 (75) um, Type 'E' Thermocouples
3-Axis Ultrasonic Anemometer
Flux Magnetometer
Tw
Ta
U2
Sampling Magnetometer
Wind Direction
Tw
Ta
U3
Pressure Sensor
Tw
Ta
U4
Mean Sea Level
Pitch and Roll Inclinometers
Wave motion package & 3 axis accelerometers
T_sea @ -0.5m
3 axis integrating accelerometers
Thermistor Chain A
T,A1
T,A2
T,A3
T,A4
T,A5
T,B1
T,B2
T,B3
T,B4
T,B5
Thermistor Chain B
T,C1
T,C2
T,C3
T,C4
T,C5
Thermistor Chain C
Counterweight, shown in deployed position.
Current Meter
Current Meter
Current Meter
Counterweight Tank (flooded for lowering and purged with compressed air to raise).
8 wire wave array
Counterweight arm shown in 'up' position for towing.
'MENTOR' Research Buoy
SEMAPHORE 1993

FIGURE 2

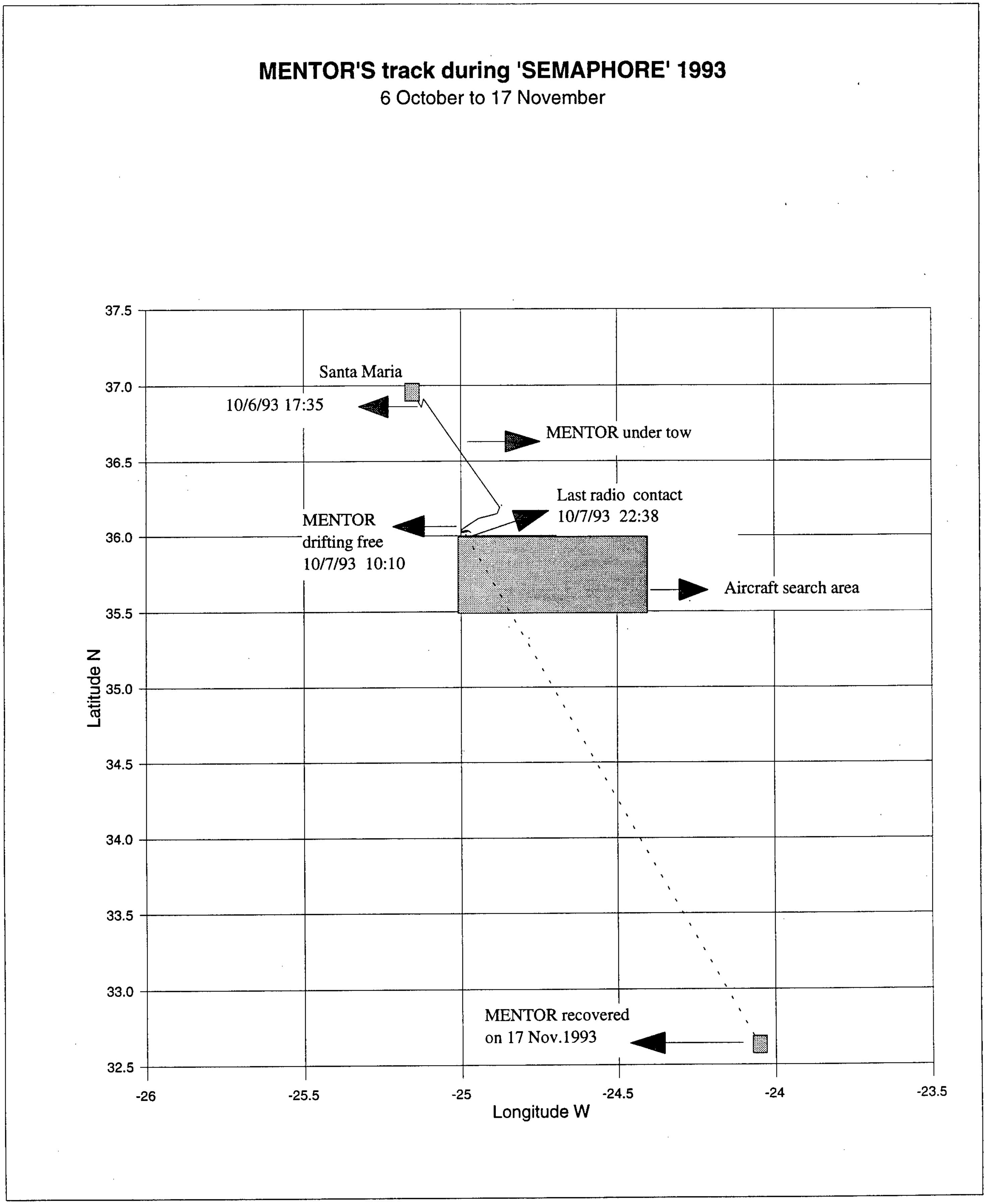

MENTOR'S track during 'SEMAPHORE' 1993
6 October to 17 November
Santa Maria
10/6/93 17:35
MENTOR under tow
Last radio contact
10/7/93 22:38
MENTOR
drifting free
10/7/93 10:10
Aircraft search area
MENTOR recovered
on 17 Nov.1993
Latitude N
Longitude W
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
-26
-25.5
-25
-24.5
-24
-23.5

FIGURE 3

Performance of the *Mentor* buoy in SEMAPHORE

W.M. Drennan and M.A. Donelan

National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario L7R 4A6, Canada

1994 January 18

Deuxième rapport dans le cadre du contrat 92/2 422 138/C

ABSTRACT

During the SEMAPHORE (Structure des échanges mer-atmosphère, propriétés des hétérogénéités de l'océan et leur répartition) experiment which took place off the Azores Islands, Portugal during the October 1993, the research buoy *Mentor* was deployed for the measurement of atmospheric profiles and fluxes, as well as various wave and current properties. During its brief cruise, *Mentor* encountered one of the strongest storms in recent local memory. We report here on the performance characteristics of the buoy and present some preliminary data.

RÉSUMÉ

Pendant l'expérience SEMAPHORE (Structure des échanges mer-atmosphère, propriétés des hétérogénéités de l'océan et leur répartition) qui se passait près des îles Açores en Octobre 1993, la bouée scientifique *Mentor* a été déployée pour mesurer les profils atmosphériques et les flux, au même temps que des propriétes des vagues et des courants. Pendant son bref voyage, *Mentor* a rencontrée une des plus fortes tempêtes que l'on se souvienne. Nous présentons ici un rapport sur la performance de la bouée, ainsi que des données préliminaires.

1. INTRODUCTION

SEMAPHORE (Structure des échanges mer-atmosphère, propriétés des hétérogénéités de l'océan et leur répartition) and its precursor SOFIA (Surface de l'océan: les flux et leurs interactions avec l'atmosphère) are experiments designed to "improve the understanding of the processes determining the turbulent and radiative fluxes at the sea surface, particularly their dependence on sea state and on mesoscale structures in the planetary boundary layer" (Katsaros and Donelan, 1993). The specific objectives include testing the surface flux-profile relations (see, e.g., Businger et al. 1971, Dyer 1974 or Donelan 1990) and determining the dependence of surface fluxes on sea state. The flux-profile relationships, usually derived from experiments over land, have not been fully tested over water, and data in high water temperature/low wind speed conditions typical of the much of the tropical ocean is particularly sparse.

The experiment took place during the month of October, 1993 near the Azores Islands in the mid-Atlantic Ocean. Amongst the special equipment deployed was a 3.2 tonne drifting buoy equipped with a 9 m mast for atmospheric profile measurements. In order to make accurate measurements of the surface fluxes and sea state, techniques developed during SWADE (Surface wave dynamics experiment – see Weller et al, 1991) and HIRES (High resolution remote sensing programme – see Herr et al, 1991) were used. In particular, the buoy was equipped with a motion sensing package, sonic anemometer and wave staff array allowing for the calculation of direct (eddy-correlation) fluxes and directional wave spectra.

SEMAPHORE was a follow-on to the SOFIA experiment of the previous spring, and the deployment of *Mentor* during SOFIA led to several conclusions (see Donelan and Drennan, 1993). The most important conclusion was that modifications would have to be made to *Mentor* to ensure that it pointed into the wind: the vane used during SOFIA was found to be inadequate for the purpose, and the buoy tended to rotate about its counterweight. To counter this, the vane was enhanced and a drogue net was designed and added to *Mentor*.

2. *Mentor* instrumentation

The equipment deployed on *Mentor* during SEMAPHORE was similar to that deployed during SOFIA. Cup anemometer speed and wet and dry bulb temperatures, each at heights of about 2, 3, 5 and 8 m above sea level, Gill wind speed and direction, atmospheric pressure, sea surface temperature, relative humidity, radiation fluxes (PSP, PIR), tilt angles, buoy heading and battery voltage were sampled by the University of Washington Campbell recorder at 1 Hz. The CCIW data aquisition system, sampling at 10 Hz, recorded the six components of buoy motion (rotations and linear accelerations), the wind velocity measured by a three component sonic anemometer and the wet and dry bulb temperature measured by a fine wire thermocouple psychrometer. The above equipment was used during both SOFIA and SEMAPHORE. During SOFIA, a three component wave staff array was deployed for the estimation of directional wave spectra. Unfortunately, one of the staffs failed and the remaining two were unable to resolve the wave directions adequately. During SEMAPHORE, a total of eight wave staffs were deployed off the port side of the bow. Six were arranged in a centered pentagon (radius 40 cm.) for the estimation of directional spectra, with a further two near the centre wire for the measurement of slopes. An infrared hygrometer malfunctioned just prior to deployment and was removed.

Prefield calibrations of the meteorological instruments and motion package/wave staffs were carried out at the University of Washington and the National Water Research Institute respectively.

3. Analysis and results

— Chronology

The recorded cruise of *Mentor* during SEMAPHORE lasted 37 hours 18 minutes and took place during one of the worst storms near the Azores this century. The principal events of the cruise are noted in Table 1. Of the 37 hours, 16 were while *Mentor* was under tow. The buoy was towed stern first so that the counter weight towed behind. Although the wave staff array was not deployed while under

tow, all other systems were operating. For much of the towing period the wind was at 90 - 120 degrees to the direction of travel, so that the profile and flux data should be good. The sonic anemometer failed about ninety minutes after the release of *Mentor* and its loss seemed to cause power problems for other data channels. Specifically, the heave, roll and voltage reference channels started drifting about 90 minutes after the failure of the sonic. This drift is thought to be related to the sonic, as the drifting of the V_{ref} was highly coincident with the sonic channels going off scale. At any rate, the signals (except the sonic) did return to normal some nine hours later. Although most of the wave staffs recorded faithfully throughout this period, the problems with the motion channels limit the time when directional wave spectra can be calculated.

Thirteen hours after the release, the buoy underwent a sudden tilt and the mast was lost several minutes later. Evidence points to the mast coming down between the port hatch and wave staff box. At that time, the significant wave height was measured at 4.3 m with wind speeds near 15 m/s. With the collapse of the mast, communication with the ARGOS satellite was lost, along with much of the scientific equipment. The computers in the hulls continued recording for a further 110 minutes (CCIW) and 5.7 hours (UW) although the signals do not help us meet the goals of the experiment. After the storm abated, a search for *Mentor* ensued. After four days of searching with aircraft and a ship, *Mentor* was assumed sunk. Six weeks later, however, the buoy was found and recovered by a French naval vessel.

— Performance characteristics

As noted above, during the SOFIA experiment *Mentor* had a strong tendency to rotate and consequently rarely pointed into the wind. A special drogue, designed to arrest the rotating motion, was installed prior to the SEMAPHORE launch. Measurements of wind direction with respect to buoy bow indicate that, after release from the ship, *Mentor* pointed at 4.7 degrees r.m.s. to the wind direction (based on 2-min averages), with a maximum 2-min deviation of 18 degrees. Clearly the drogue and enlarged vane served their purpose well.

During its brief (recorded) cruise, *Mentor* was subjected to some of the roughest seas the area had experienced for years: seas which were well beyond the

expected limits of both the buoy and its instrumentation. The ultimate result of this was the collapse of the mast and the failure of the recording systems. However, lesser problems were also encountered with the motion sensing equipment. Specifically, r.m.s. values of surge and sway exceeded 1 m/s/s, with occasional peak values greater than the 3 m/s/s (5 V) limitations of the data aquisition system. Accelerations were simply considerably higher than expected. Although this resulted in occasional clipping of the signals, experience indicates that neither fluxes nor spectra will be badly effected. Typical pitch angles were $\pm 4°$ r.m.s with maximum pitch angles of over $15°$. Variations in roll were similar, although the roll sensor experienced problems with spikes. These deviations were well within the range of the angular rate sensors.

— Eddy correlation fluxes

The eddy correlation analysis follows that of Anctil et al (1994). The anemometer signals are first corrected for the axial and rotational motions of the buoy – see, Figure 1 which shows the corrected vertical velocity plus the three components from which it was computed. The fluxes are then found by calculating the correlation between the vertical velocity fluctuations with the fluctuations in horizontal velocity (momentum flux), air temperature (sensible heat flux) or humidity (water vapour or latent heat flux). The $u - w$ cospectrum (i.e. momentum flux) corresponding to the above appears in Fig. 2.

As mentioned above, the sonic anemometer failed after some eighteen hours, during sixteen of which the ship was being towed. Velocity profile data exist throughout this period, so that a test of the flux-profile relations can be made albeit with a limited range of data. In order to made use of the profile data while under tow, the ship speed is required. At the present time, this information is lacking, but it has been requested. We present below measurements from the 34 minute period 10h42 - 11h16 on 7 October (JD 280), corresponding to the run discussed briefly above. Figure 3 shows the ten minute average wind speed profiles, plotted in semilog coordinates. Each four point profile gives three independent estimates of $u_* = \kappa z \partial U / \partial z$, where U, z and κ are the mean wind speed, the height above the mean surface level and von Kármán's constant (taken to be 0.41) respectively. Averaging the three profiles yields $u_*(2.44, 3.66, 6.52 \text{ m}) = 0.526, 0.491, 0.441$ m/s

for an average value of 0.486 m/s. This compares with an eddy-correlation estimate of 0.44 m/s. Although the air-sea temperature difference at this time was small, conditions were unstable with an estimated Obukhov length, L, of − 214 m. With $\zeta = z/L = -0.04$, Donelan (1990) predicts

$$\phi_M(\zeta) \; = \; \kappa z u_*^{-1} \partial U / \partial z \; = \; (1 - 17\zeta)^{-1/4} \; = \; 0.878.$$

The value from the data yields $\phi_M = 0.916$. The entire data set should yield some forty or more estimates based on 17 minutes of data, mostly under near neutral or unstable conditions. Although the stability range is small, some verification of the over-land flux-profile relations should be possible.

The air temperature (via the dry bulb of the psychrometer and sonic anemometer) and humidity (via the psychrometer) were also measured, so the heat and moisture flux-profile relations can also be verified – if the data prove to be good. Unfortunately two of the four dry bulb thermometers failed so that temperature and humidity profiles are typically sparser than their velocity counterparts.

— Directional spectra

The spectra were calculated following the method of Drennan et al (1994) in which the wave staff signals are first corrected for the buoy motion. As an example of the motion correction, Fig. 4 shows the wave staff signal as measured, along with the corrected (true) surface elevation and the terms going into the correction. The corrected signals were then used as input into a maximum likelihood method algorithm based on Isobe et al (1984). The MLM analysis was carried out on blocks of length 512 (5 Hz data) using 5° angular resolution. Doppler shifting of the frequencies due to the slow drift of the buoy was assumed to be neglible.

Although the number of spectra are limited, *Mentor* records the wave development during a rapidly growing sea : during the ten hours the array was deployed, the significant wave height increased from 2.8 to 4.5 m. Just prior to the collapse of the mast, a single wave of height 9 m was recorded. Examples of directional spectra spanning this period are reproduced in Figure 5.

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Table 1 - Chronology of Mentor during SEMAPHORE, 1993 October 6-8

Day	Time	Mentor	UW Campbell	CCIW
279	15:42		start recording	
	16:54			start recording
	17:36	leave harbour		
280	05:06	course correction		
	05:12		Td (3m) failure	
	09:26	release from ship		
	09:32		Td (8m) failure	
	10:02			wave staffs lowered
	11:33			sonic failure
	13:00			heave drifting
	14:10			Vref/roll drifting
	22:04			heave/Vref/roll recover
	22:44	sudden 0.5 m tilt		staffs clipped
	22:52	GPS lost	Mast channels fail	sway jumps 0.5V
281	00:35			heave/surge/roll bad
	01:32			end recording
	04:36		end recording (SST)	

LIST OF FIGURES

NOTE: THESE FIGURES WERE NOT INCLUDED INTENTIONALLY, SINCE THEY ARE SUPERCEEDED BY THE NEWER ONES PROVIDED IN DRENNAN & DONELAN (1995).

In *Second International Conference on Air-Sea Interaction and on Meteorology and Oceanography of the Coastal Zone*, September 22-27, 1994, University of Lisbon, Portugal.

P9.10 FLUX GRADIENT MEASUREMENTS FROM A CATAMARAN BUOY IN SEMAPHORE

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University of Washington, Seattle, Washington, 98195, U.S.A.

William M. Drennan and Mark A. Donelan
Canada Centre for Inland Waters,
Burlington, Ontario, Canada

1. INTRODUCTION

During the SEMAPHORE "Structure des Echanges Mer Atmosphere Proprietes des Heterogeneties de L'Océan leur Repartition" (Structure of Exchanges with the Marine Atmsophere, Properties of Heterogeneities of the Ocean and their Repartition) experiment in the fall of 1993, a large catamaran buoy, the MENTOR, was set adrift in the Azores region. The purpose of the buoy was to provide measurements for testing flux-profile relations over the sea, and to measure the influence of sea state on the turbulent fluxes and atmospheric profiles and the effects of atmospheric and radiative fluxes on near surface temperature structure in the ocean. In addition, the buoy measurements were to provide an anchor point for calibrating mesoscale bulk surface flux estimates over the SEMAPHORE domain and to provide intercomparison data for dissipation estimates of fluxes from the R/V *Le Suroit.* Loss of the instrument mast in a severe storm on October 7 cut short the usefulness of the buoy in this regard. Miraculously, the hulls of the buoy survived even though part of the stabilizer was also lost, as were the vane and drogue. Both a fast recording unit for turbulence and wave information and a recording unit for the mean atmospheric profiles inside the two hulls were rescued. These data allowed calculation of vertical profiles of wind speed temperature and humidity as well as the turbulent fluxes and directional wave spectra during a period of increasing wind speed.

From this type of data the coefficients in the flux profile relations (e.g. Businger et al., 1971) can be evaluated. These data from a subtropical fall condition will be combined with data from the pilot experiment in the same region, July, 1992, and other data sets from Lake Ontario and Lake Washington to test whether the currently used flux profile relations originally derived from the Kansas experiment can be used intact over water surfaces.

2. DATA COLLECTION

MENTOR carried a complete suite of instruments for measuring air sea interactions : atmospheric profile and turbulence sensors, for wind, temperture and humidity, short and longwave radiometers, an 8 wire pentagon shaped wave staff array with 3 closely spaces wires in the center allowing slope determinations. Three nested thermistor chains provided temperature and conductivity measurements to 40 m depth. A complete motion sensing package determined the linear and angular accelerations of the frame of reference for the velocity and wave sensors, and an ARGOS positioning device allowed corrections for the mean displacement velocity of the buoy during a data run. Figure 1 is a schematic of the buoy with its 8 m tall instrument mast and 12 m floodable counter weight. Not shown in this figure is the 4 m^2 wind vane positioned at the rear of the buoy and the 26 m long drogue placed at the upwind end below the profile booms. The drogue, constructed according to the design of Pingree (Pingree and LeCann, 1992) and the vane fulfilled the purpose of turning the profile sensors into the mean wind direction. Several Taddle Tale recorders collected the turbulence, wave staff and motion package data at 10 Hz, while a Campbell recorder sampled the slow sensors at 1 Hz.

3. RESULTS AND DISCUSSION

Examples of observed atmospheric profiles and covariance spectra will be presented on the poster.

The rather noise free environment using battery powered measuring and recording

systems allows clean spectra to be obtained. The exceptionally open structure of this platform also assures minimal flow distortion of the profiles.

ACKNOWLEDGMENTS

The work was supported by our Portuguese collegues,A.G. Fiuza, M.C. Rufino and J.H. Diaz of the University of Lisbon and by F. Weller, J.Gabriele, H.Seville, and J. Tournadre. We thank Capt. Bothelo and his crew . Financial support provided by the National Science Foundation, the Office of Naval Research, the ARM program of the Department of Energy,the PAMOS program of Institut des Sciences de l' Universe, and IFREMER is gratefully acknowledged.

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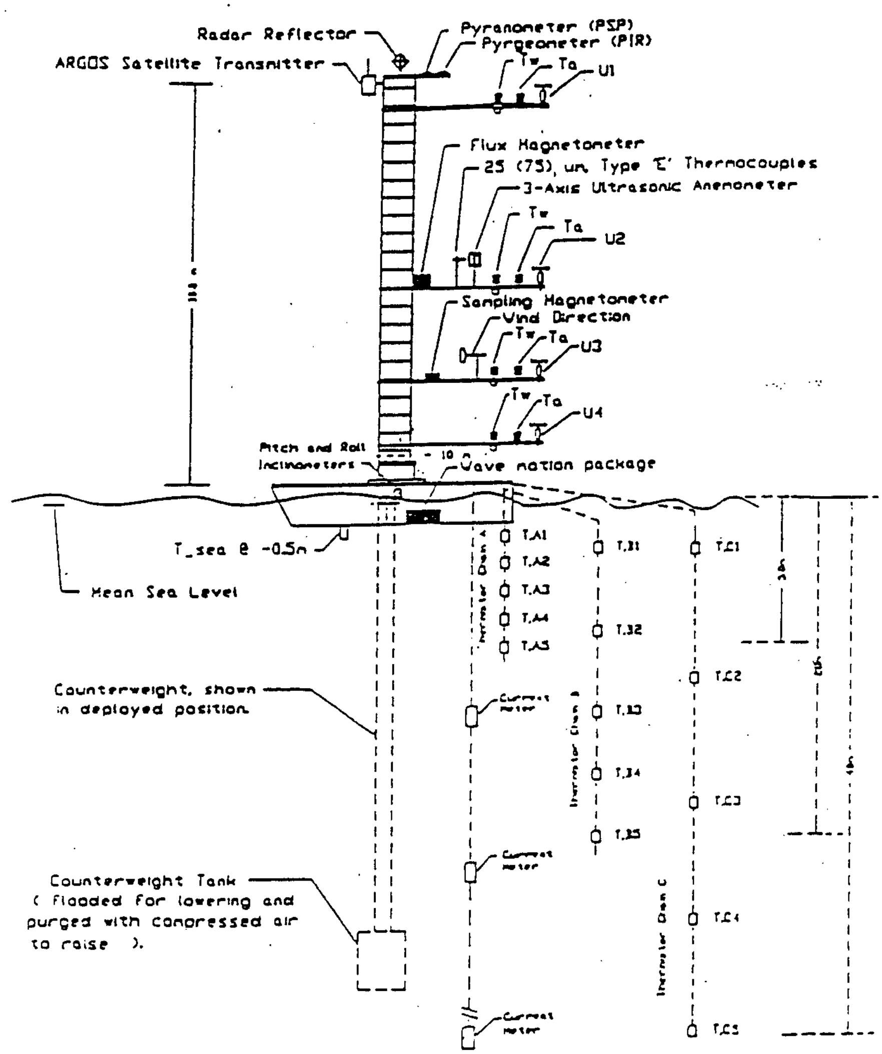

Figure 1 : Schematic of the buoy Mentor with its suite of flux-profile motion sensing instruments.

Flux and profile data from *Mentor* in SEMAPHORE

W.M. Drennan and M.A. Donelan

National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario L7R 4A6, Canada

Submitted 1995 March 17

Troisième rapport dans le cadre du contrat 92/2 422 138/C

ABSTRACT

Due to damage sustained during a severe storm, the drifting catamaran buoy deployed during the SEMAPHORE (Structure des échanges mer-atmosphère, propriétés des hétérogénéités de l'océan et leur répartition) experiment of autumn, 1993, recorded only a few hours of data. A larger body of data was collected while the buoy was under tow. Since these data were not expected to be used, their quality is evaluated and data considered to be reliable are presented.

RÉSUMÉ

À cause d'une tempête sévère, la bouée catamaran *Mentor*, qui flottait à la dérive pendant l'expérience SEMAPHORE (Structure des échanges mer-atmosphère, propriétés des hétérogénéités de l'océan et leur répartition) de 1993, a subi des dommages, limitant la période de collection des données à quelques heures. Une collection des données plus importantes a été prise pendant le remorquage de la bouée. Malgré que nous n'avions pas l'intention d'utiliser ces données, elles ont été quand même évaluées et les bonnes données sont présentées.

1. INTRODUCTION

During the SEMAPHORE (Structure des échanges mer-atmosphère, propriétés des hétérogénéités de l'océan et leur répartition) experiment of autumn, 1993, the free-drifting catamaran buoy *Mentor* was deployed off the Azores Islands. The buoy was equipped for the measurement of turbulent fluxes and profiles in the atmospheric boundary layer, along with wave and ocean surface properties, with the goal of determining the effect of waves on the surface flux-profile relations. Unfortunately, as reported in Katsaros *et al.*(1994), most of the instruments were lost during a severe storm early in the experiment. As a result, only a few hours of flux-profile data were collected while the *Mentor* was drifting. A further sixteen hours of data were gathered with the buoy under tow, en route to its release site. Given that these conditions were outside the expected operating range of *Mentor*, factors likely to lead to data contamination are evaluated. Data considered to be reliable are then presented.

2. *Mentor* instrumentation

The equipment deployed on *Mentor* during SEMAPHORE was similar to that deployed during SOFIA. Cup anemometer speed and wet and dry bulb temperatures, each at heights of about 2, 3, 5 and 9 m above sea level, Gill wind speed and direction, atmospheric pressure, sea surface temperature, relative humidity, radiation fluxes (PSP, PIR), tilt angles, buoy heading and battery voltage were sampled by the University of Washington Campbell recorder at 1 Hz. The CCIW data acquisition system, sampling at 10 Hz, recorded the six components of buoy motion (rotations and linear accelerations), the wind velocity measured by a three component sonic anemometer and the wet and dry bulb temperature measured by a fine wire thermocouple psychrometer. The above equipment was used during both SOFIA and SEMAPHORE. During SOFIA, a three component wave staff array was deployed for the estimation of directional wave spectra. Unfortunately, one of the staffs failed and the remaining two were unable to resolve the wave directions adequately. During SEMAPHORE, a total of eight wave staffs were deployed off the port side of the bow. Six were arranged in a centered pentagon (radius 40 cm.) for the estimation of directional spectra, with a further two near the centre wire for the measurement of slopes. An infrared hygrometer malfunctioned just prior to deployment and was removed.

Prefield calibrations of the meteorological instruments and motion package/wave staffs were carried out at the University of Washington and the National Water Research Institute respectively.

3. Analysis and results

3.1 Data summary

As reported in Drennan and Donelan, 1994, there were a total of 36 hours, 54 minutes of data recorded by the U. Washington Campbell and 32 hours, 38 minutes of data recorded by the CCIW system. The majority of these data, however, were collected while the *Mentor* was under tow. These towed data represent some 60% of the profile data and almost 90% of the eddy-correlation flux data. Since the use of these data was not anticipated, their quality must first be evaluated.

During towing, the 4.5m long *Mentor* was approximately 14m behind the 25m fishing boat *Mestre Bobisha*. These distances have been estimated from photographs — see Fig 1 — and confirmed by Joe Gabriele (CCIW field technician). The *Mentor* was towed stern first, with the counterweight dragging behind on the surface. The superstructure of the *Mestre Bobisha* was approx. 7m above mean sea level, with masts, antennae etc. projecting up an additional 5m, well above the level of the *Mentor* mast. The exact heading and speed of the *Mestre Bobisha* during towing were not logged, although the heading information has been recovered from the magnetometer on board the *Mentor* and occasional times and positions from ARGOS were noted. The course was southerly for the first eight hours, then veering along an arc towards the east for the next four hours. A 180 degree course correction was then made, with an initial heading west, gradually veering along an arc towards the south. A mean ship speed of 5 knots throughout the cruise is assumed.

Although the data acquisition systems were running while the *Mentor* was under tow, this was done for operational convenience: the useful data were to be collected while the *Mentor* was freely drifting. However, the early failure of the sonic anemometer and heave acceleration sensor allowed for only a few hours of directional wave spectra and eddy correlation flux data while the collapse of the mast resulted in only thirteen hours of profile data being collected. With the paucity of drifting data it was hoped that the fifteen hours of towed data, including profile and eddy-correlation flux measurements, but not directional wave spectra, could be

used. Unfortunately, however, this does not appear to be the case. Although it was recognized that relative winds coming over the ship would result in significant disturbances to the turbulent flow at the buoy, winds coming from behind the *Mentor* (i.e. blowing towards its bow) or from the side should not have the problem. According to Fig. 2, there are no cases of the relative wind coming from behind, although there are many hours of data with the relative wind blowing from port or starboard. The *turbulence* recorded by the *Mentor* sensors is free of ship induced disturbance at these angles, but there will be significant disturbance to the potential flow field due to compression of the streamlines around the large blunt body, the *Mestre Bobisha*. In order to be free (99%) of these effects, the *Mentor* should have been of the order of fifty to one hundred metres behind the *Mestre Bobisha*. We note that the *Mentor* was initially designed and used as a towed catamaran (Badgley *et al.*, 1964), being towed some 150 - 400 metres behind the ship during the early Indian Ocean cruises. Unfortunately, during SEMAPHORE the towing distance was fourteen metres, less than one ship length away from the *Mestre Bobisha*. Due to the shape of the *Mestre Bobisha*, the effects of the potential flow disturbance would be expected to be greatest close to the surface, with the apparent wind speeds greater that the actual ones. This would have the effect of reducing the slope of the logarithmic profile. As seen in Fig 3., the profiles were sometimes vertical (no wind speed increase with height) or reversed (a wind speed decrease with height) indicating probable disturbances of the type described. Note that the profiles seen in Figure 3 have been corrected for the ship speed according to

$$U_{wind}^2 = (U_{rel}\sin\theta)^2 + (U_{rel}\cos\theta - U_{ship})^2$$

where θ represents the (relative) wind direction as seen by the buoy (i.e. as in Fig. 2).

Although these profile data were rejected for flow disturbance reasons, there are other problems associated with making cup profiles from a moving platform (towed or not). The problems with cup overspeeding due to differential acceleration/deceleration rates ($u-$error) are well known (see MacCready, 1966) and can be largely overcome by using low-inertia cups (e.g. Frenzen and Vogel, 1992). A second error, the $w-$error, arises from deviations of the flow from the vertical, and the resulting shading of the rear cups. According to MacCready, errors of 2% for deviations of 15° and over 8% for deviations from the horizontal of over 25° are typical for standard cup anemometers. Although this is already a problem for stationary anemometers, for moving anemometers the problem can become quite

serious because the angular deviation is that of the wind plus that of the anemometer. In order to determine the magnitude of the error, wind tunnel tests should be carried out using the *Mentor* setup.

A related problem arises due to the nondirectionality of the cup anemometer: an oscillatory flow, such as that induced by pitching and rolling of the platform, will be rectified by the anemometer and hence the platform motion will tend to result in overestimated mean winds. This effect increases with distance from the axes of pitch and roll, and so would result in increased profile slopes. The magnitude of this error can be estimated, since the pitch and roll time series are recorded. Furthermore, these time series (r.m.s.) could be used to correct the profile winds if the angular motions were not excessive. It must be noted though that these corrections are second order: the potential flow disturbance is first order.

3.2 Profiles and eddy correlation fluxes

During SEMAPHORE, an objective was to make simultaneous measurements of profiles (velocity, temperature and humidity) and eddy-correlation fluxes and thence to test the flux-profile relations. Integrating the surface gradient relations and assuming negligible surface drift, we have

$$U_z = \frac{u_*}{\kappa}\left[\ln(z/z_o) - \psi_u(z/L)\right]$$

where $\psi_u(z/L)$ is a flux-profile relation that serves to correct to logarithmic profiles for stability. L is the Monin-Obukhov length. These relations have been derived over land (see, e.g., Donelan 1990 or Dyer 1974) but they have never been verified over the sea. Unfortunately, the above mentioned problems with the towed data and the failure of the sonic anemometer after only two hours of free drifting has made this goal impossible to realize. At best, the data from the four 17-min runs appearing below in Table 1 can be incorporated into a larger data set sometime in the future.

Table 1: SEMAPHORE flux-profile data.

Run number	29-1	29-2	30-1	30-2
u_* [m/s]	0.353	0.411	0.454	0.492
$\kappa z \partial U/\partial z$ [m/s]	0.430	0.476	0.463	0.465
L [m]	-161	-212	-193	-181
U_9 [m/s]	10.36	10.67	10.44	10.40

In Fig. 4 the spectra of the horizontal and vertical wind velocity components, S_{uu} and S_{ww} respectively, along with the cospectra S_{uw} are shown. The velocity components have been corrected for buoy motion following Anctil *et al.*, 1994. The profile measurements are corrected for the rocking of the platform according to $U_c = U/(1 + (z < \dot{\theta} > /2U)^2)$ where $< \dot{\theta} >$ is the r.m.s. angular motion.

Although we can not test the flux-profile relations by independent measurement of profiles and friction velocity, if we assume the validity of existing relations, the friction velocity can be determined from the profile data. We use the relations of Donelan (1990). While free drifting, the *Mentor* recorded some 2.5 hours of profile data using cup anemometers at 1.8, 2.8, 4.8 and 8.85 m. Given any two points, a and b on the profile, u_* can been readily determined as:

$$u_{*ab} \;=\; \kappa\,(U_a - U_b)/\left((z_a - z_b)/(z_a z_b)^{-1/2} - (\psi_u(z_a/L) - \psi_u(z_b/L))\right).$$

Von Kármán's constant κ is taken to be 0.4. We use the weighted average,

$$u_* = (2u_{*41} + u_{*42} + u_{*31})/4.$$

The 38 4-minute average u_* values calculated as per above are plotted against 10 m neutral wind speeds in Figure 5. Also shown is a curve of friction velocities calculated using the drag coefficient formulae of Large and Pond (1981).

3.3 Directional spectra

An eight element wave gauge array situated off the port side of *Mentor* was deployed for some twelve hours after the release of the buoy from the *Mestre Bobisha*. During this time period, the wave staff data are generally good, although as time goes on, and the sea state builds (from 2.8 to 4.5 m significant height), there is more and more drop out and clipping of the signals from the staffs furthest from the roll axis of the buoy. The outermost staff is consequently unusable, and the next two become more and more useless as the roll of the buoy (typically $\pm 4^\circ$ rms, but with 15° excursions) increases with the sea state.

Although the wave staffs functioned well, the same is not true of the buoy motion sensors: the heave sensor started drifting 90 minutes after the sonic anemometer failed, and the roll sensor followed an hour later. Both devices returned

to on-scale over ten hours later and operated for a further 45 minutes at which point the mast failed and most systems ceased operation.

As pointed out by Drennan *et al.*(1994), a reconstruction of the directional wave spectrum requires the full motion of the buoy and hence this is not possible for much of the period. Directional spectra can be estimated during two intervals: after initial deployment of the wave staff array (JD 280, 10h30-13h00) and prior to the failure of the mast (JD 280, 22h00-23h00). These appear in Fig. 6a-c and should replace the preliminary (and incorrect) spectra shown in Drennan and Donelan (1994). The calculations were done according to Drennan *et al.*(1994), assuming negligible drift velocity. Each Figure shows three subplots: the 2-dimensional frequency spectrum, $S(f,\theta)$, $S * f^4$ and the 1-dimensional spectrum. The figures are in geophysical coordinates (north and east at top and right, respectively), with the waves shown in the direction of propagation. The wind in indicated in the direction of the arrow, with the scale 10 m/s per radial unit.

At 10h, the spectra show a strong 11-sec swell propagating towards the south-east, against the wind. The wind sea is building up, showing a 5-sec peak by 10h42. Note that the spike appearing at 0.4Hz, 350 deg. in the 10h06 plot is likely spurious. By 22h, the significant height has increased to 5 m. Although the spectra are dominated by spikes (e.g. 0.2 Hz at 0 degrees) which are likely spurious, the swell appears to have shifted some 60 degrees to the east. This latter spectrum is however based on only three staffs, and is estimated during the brief period that the heave and roll sensors returned on-scale, after many hours of 'floating means'. It is, however, difficult to judge if the sensors were functioning normally and the estimated spectra are therefore of dubious quality.

4. Conclusions

Our analysis of the data from the *Mentor* in SEMAPHORE permits us to draw the following conclusions.

- The meteorological and wave measuring system and recorders functioned well in winds up to 17 m/s and waves over 5 metres in significant wave height.

- The failure of the buoy appears to have been due to mechanical collapse of the mast and subsequent electrical short-circuiting of various systems.

• The wave gauge array yields reasonable directional spectra. Although there was no standard against which to compare these estimates, the directional spread of the waves is comparable to similar high-resolution measurements on other platforms.

• Profile measurements of the friction velocity are in general agreement with fully developed formulae. They do, however, indicate an enhanced stress especially at higher wind speeds. We believe that this is due to stronger forcing of undeveloped waves on a rising edge of a storm. There are, however, some difficulties with measurements using cup anemometers on a rocking platform. We plan to establish the degree of distortion to the profiles using wind tunnel testing.

The *Mentor* is a good platform for air-sea interaction in calm and moderate seas. It probably should not be used in seas of significant height in excess of two metres.

The flux and profile data gathered are valuable for near neutral – weakly unstable conditions, and further experiments should be done to extend the data set to a wider range of stabilities and wave ages.

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Figure Captions

Figure 1. Photograph of *Mentor* under tow.

Figure 2. Wind direction with respect to *Mentor* bow during towing.

Figure 3. Four 4-min wind profiles from *Mentor* while under tow.

Figure 4. Wind velocity spectra and co-spectra from sonic anemometer.

Figure 5. Profile friction velocities versus wind speed.

Figure 6. Directional spectra from wave staff array on *Mentor* at 10h06, 10h42 and 21h58 on JD 280, 1993. Top plots show the directional spectrum $S(f,\theta)$ with north at the top. The dotted circles have 0.1 Hz spacing. Energy is shown in the direction it is propagating towards. Wind direction is given by the arrow with a scale of 10 m/s per radial line (0.1 Hz). The lower left plots show $S \times f^4$ to emphasize the wind sea. The 1-D spectrum is shown in the lower right.

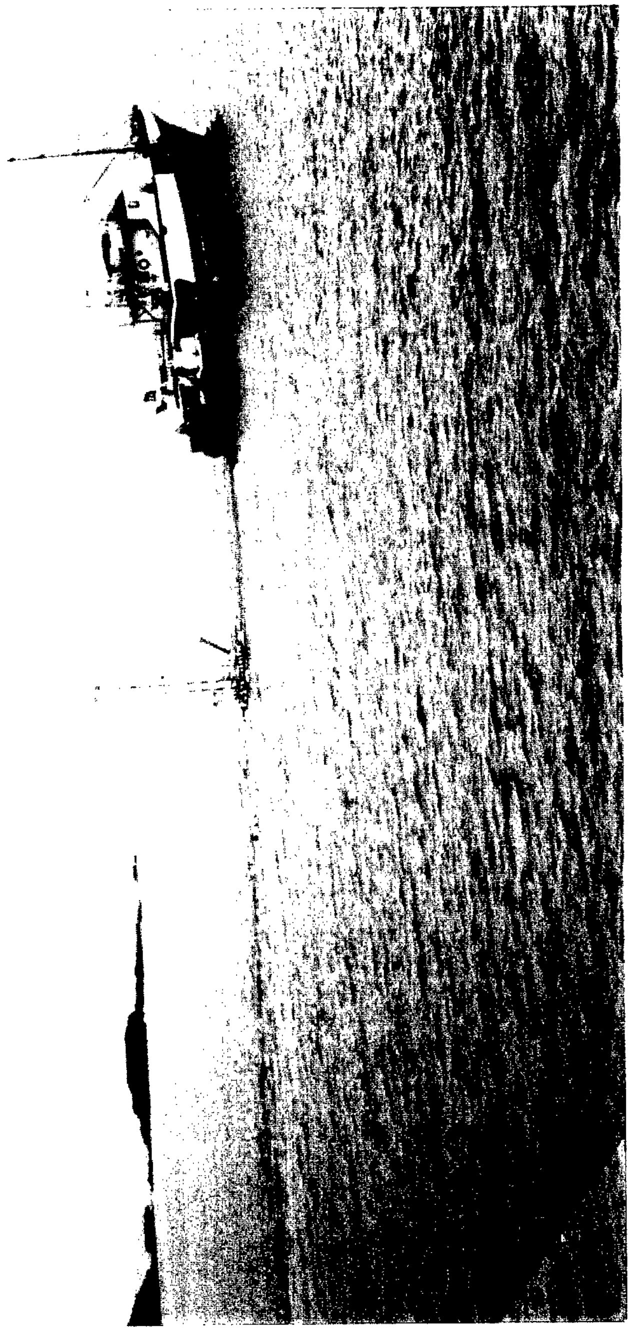


FIGURE 1

Fig2: Wind direction with respect to Mentor. UWash (-), NWRI (o)

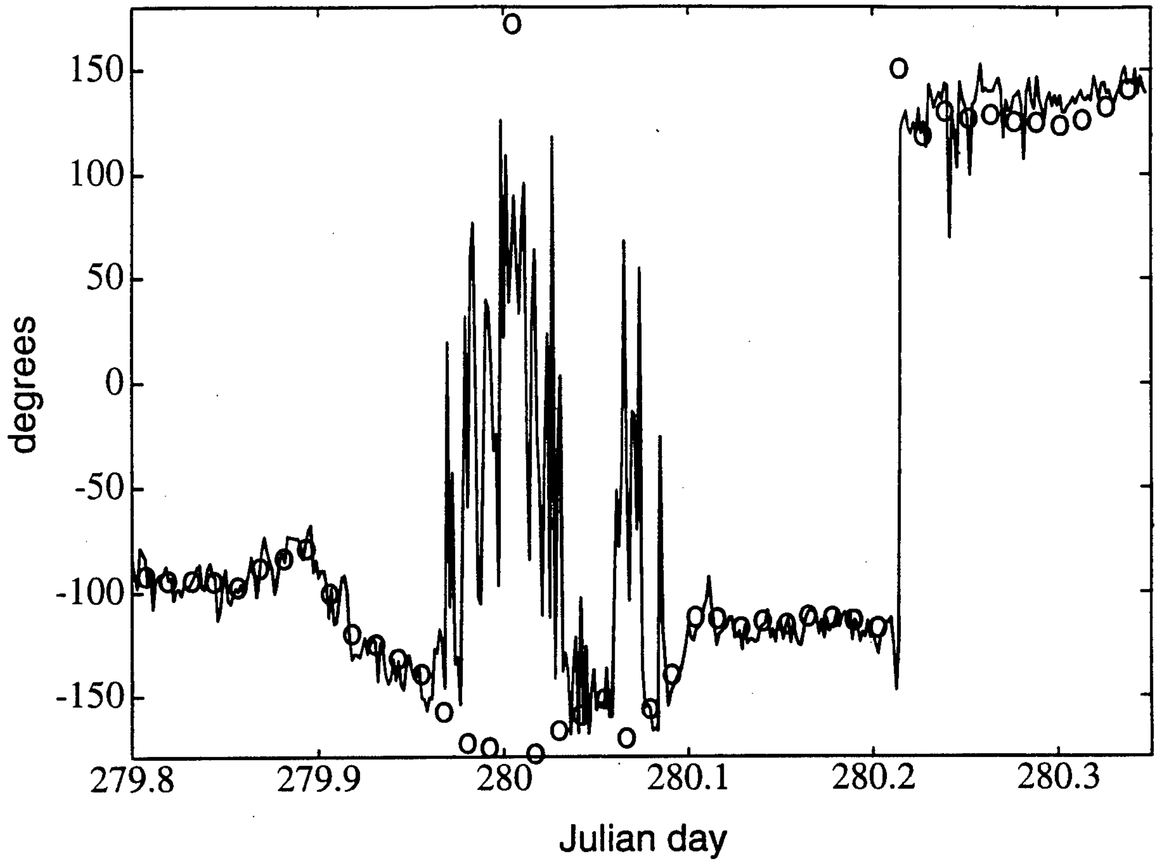


FIGURE 2

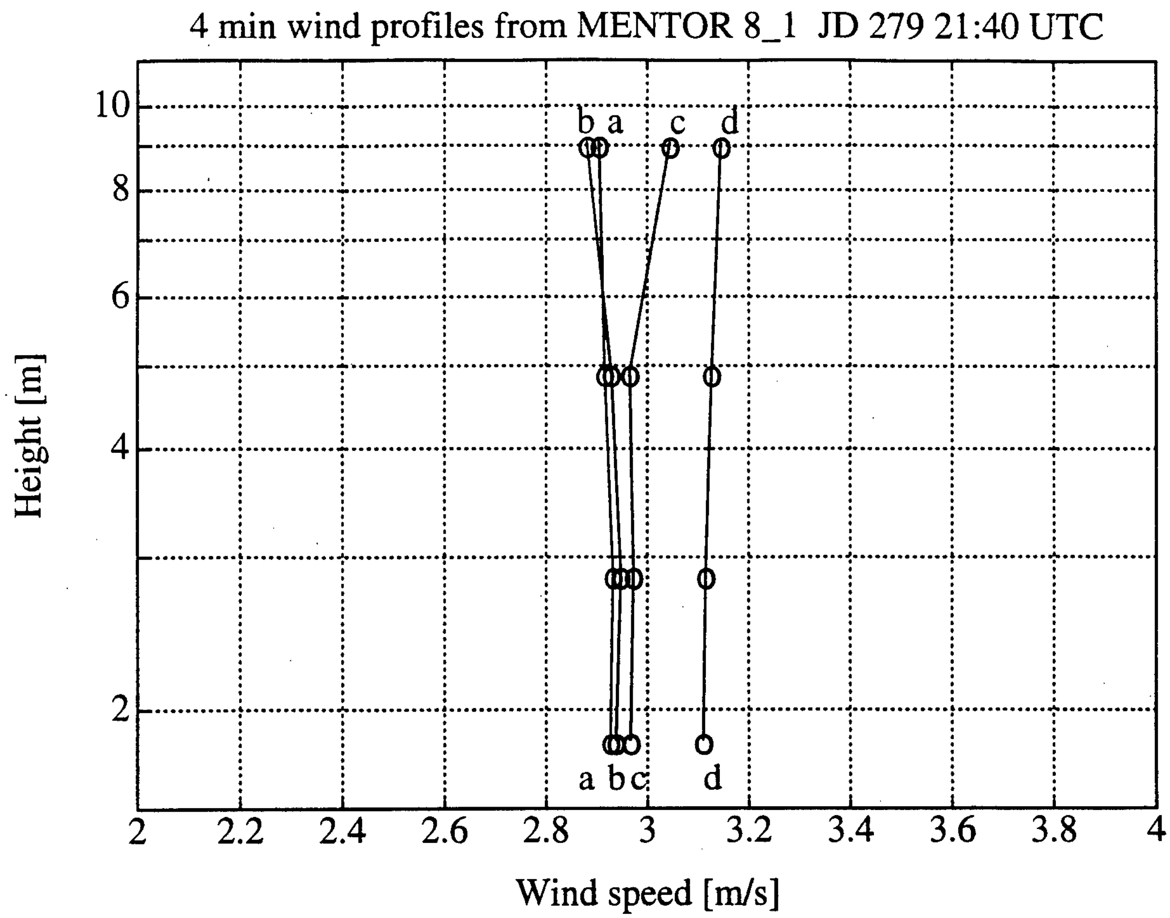
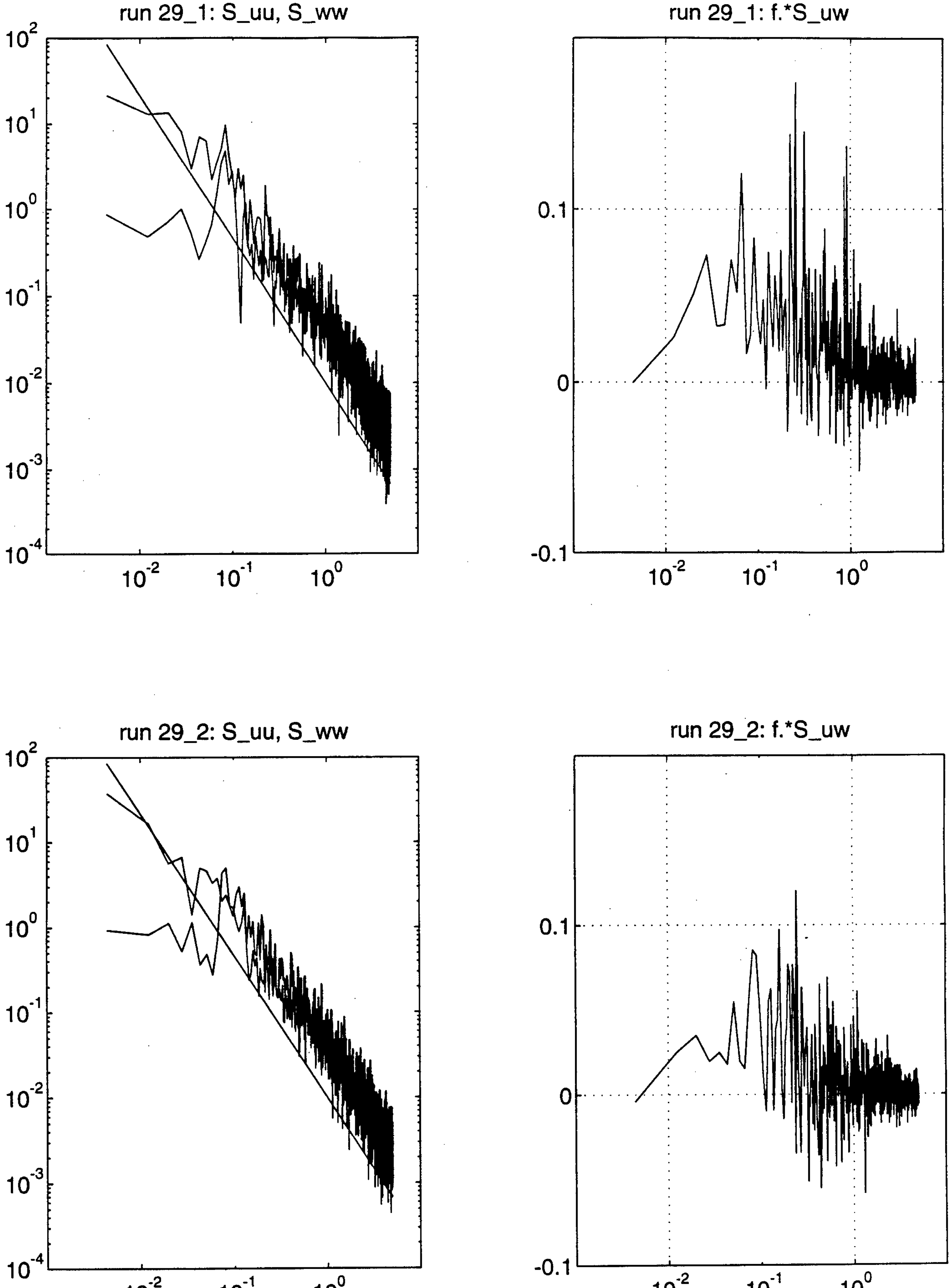
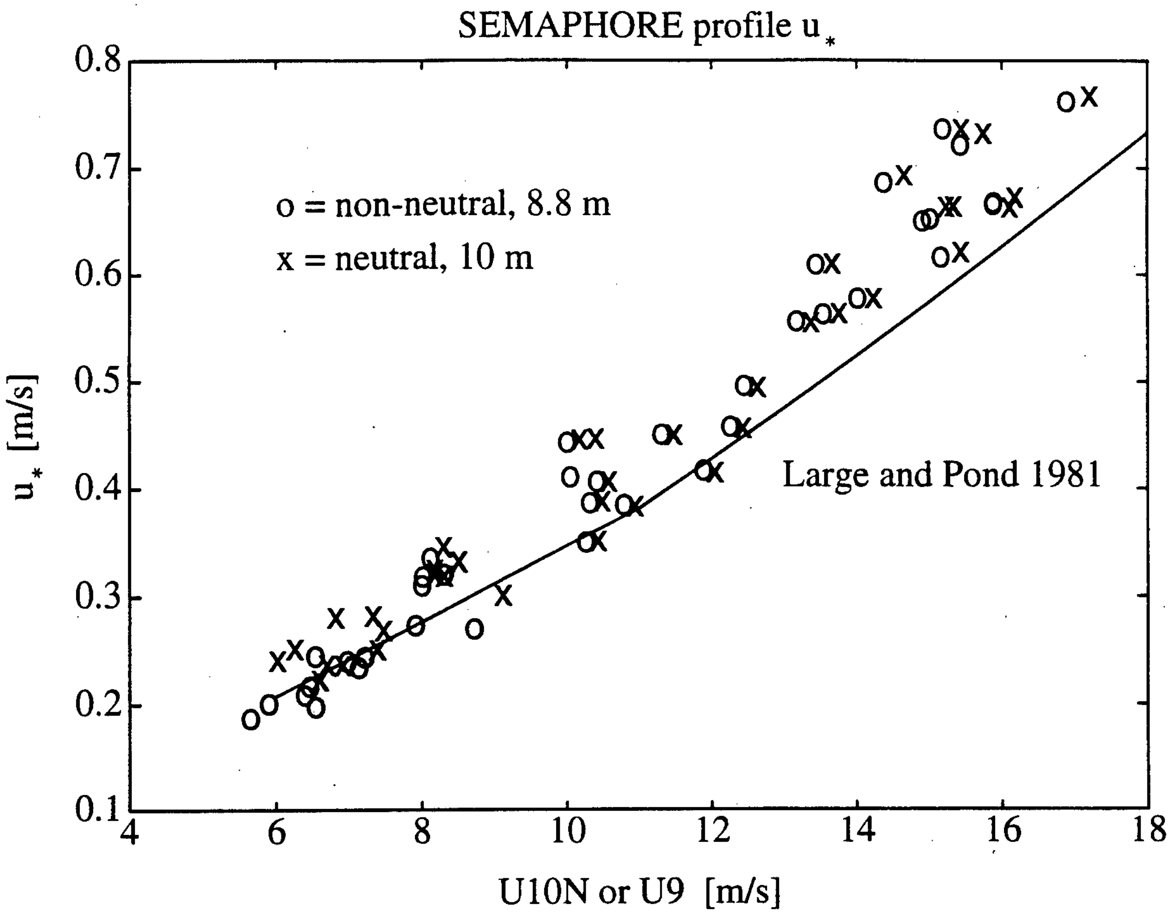

4 min wind profiles from MENTOR 8_1 JD 279 21:40 UTC
Height [m]
10
8
6
4
2
b a c d
a b c d
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
Wind speed [m/s]

FIGURE 3



run 29_1: S_uu, S_ww
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^0
run 29_1: f.*S_uw
0.1
0
-0.1
10^{-2}
10^{-1}
10^0
run 29_2: S_uu, S_ww
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^0
run 29_2: f.*S_uw
0.1
0
-0.1
10^{-2}
10^{-1}
10^0

FIGURE 4



SEMAPHORE profile u_*
o = non-neutral, 8.8 m
x = neutral, 10 m
Large and Pond 1981
u_* [m/s]
U10N or U9 [m/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
4
6
8
10
12
14
16
18

FIGURE 5

SEMAPHORE/Mentor 29 JD 280 10:06 Z

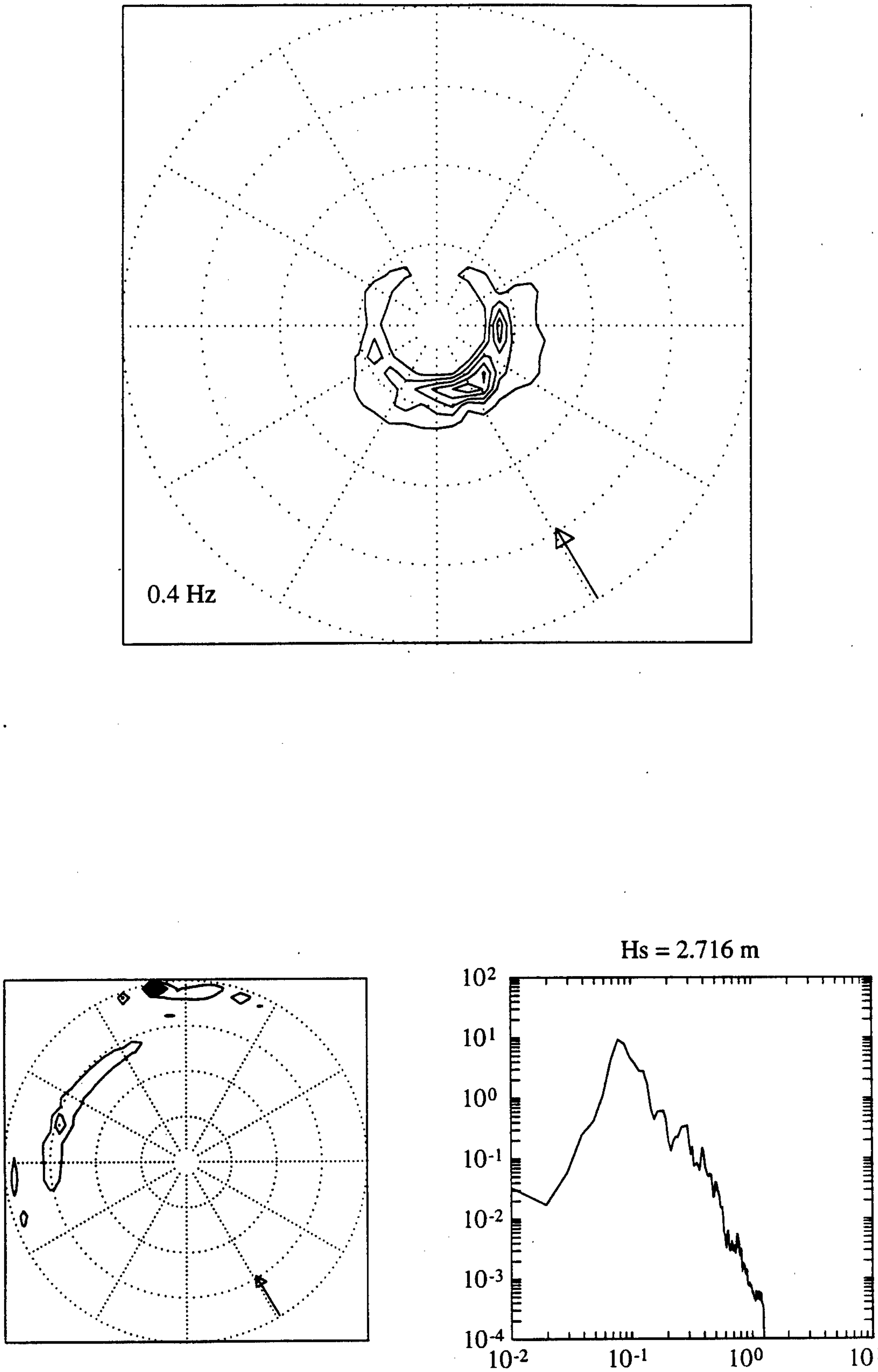
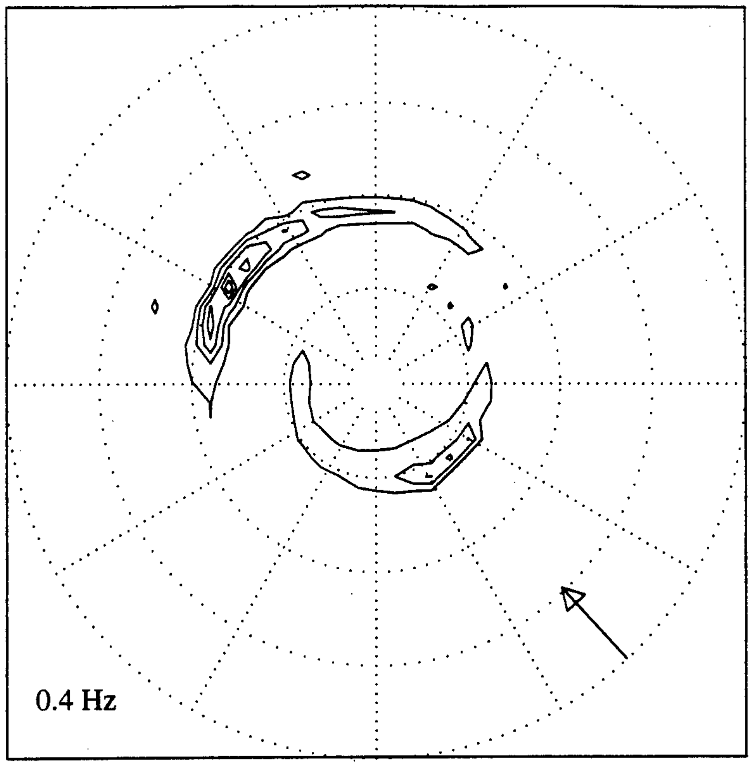
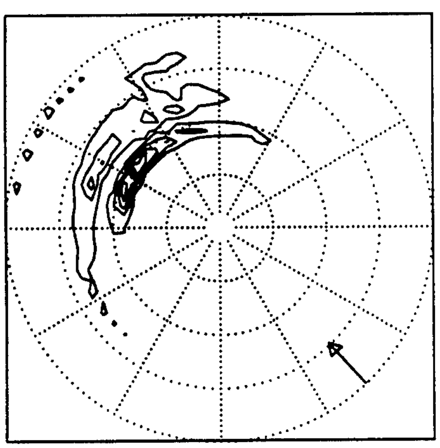


FIGURE 6 (a)

SEMAPHORE/Mentor 30 JD 280 10:42 Z





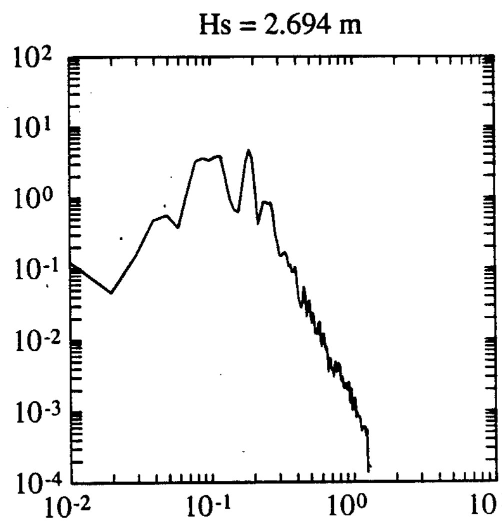
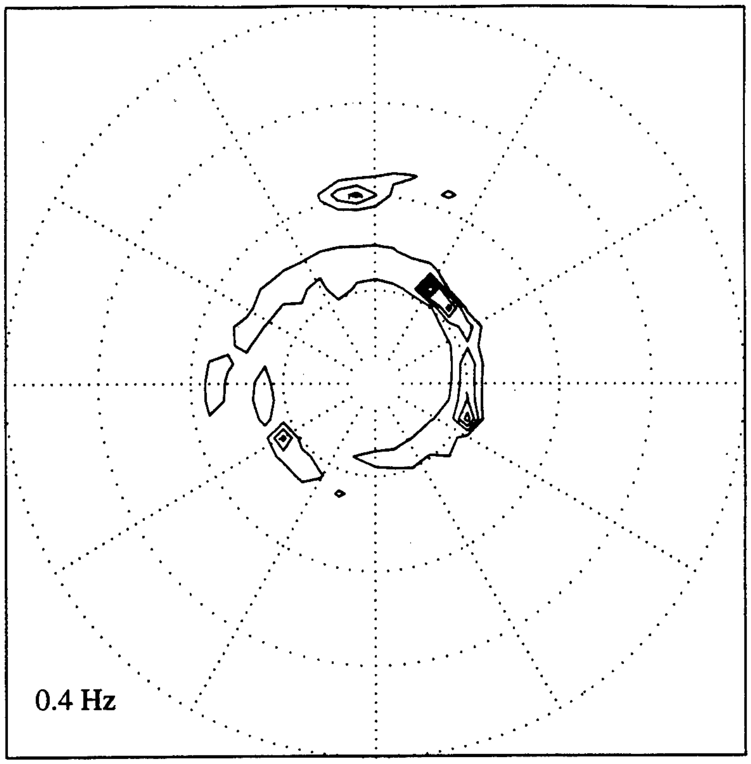
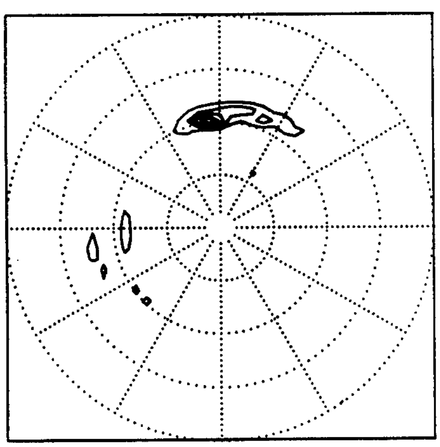


FIGURE 6 (b)

SEMAPHORE/Mentor 49 JD 280 21:58 Z





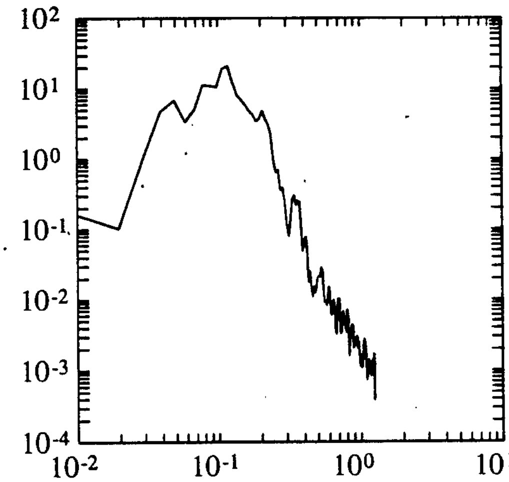


FIGURE 6 (c)